Allowable Stress for Glass

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INTRODUCTION

Weiderhorn (Reference 1) has estimated that the theoretical cohesive strength of silica glass is of the order of 3 x 10^6 psi. The highest measured values for the strength of glass (glass fibers tested in a vacuum) approach this value. On the other hand, values normally associated with the engineering or practical strength of glass are approximately 0 to 1000 times lower than the theoretical cohesive strength. This discrepancy between the theoretical and the practical strength of glass is attributable to the brittle nature of the material. Stress concentrations at the tips of existing flaws, especially surface flaws, are not relieved by plastic yielding of the material. For this reason glass always fails in tension when these flaws grow (under sustained loading) to some critical size. Thus, the surface condition of the glass is the most important single factor influencing the breakage strength of any glass part. The following factors are known to materially influence the practical strength of glass parts.

1. Part Size. Even though the intrinsic strength of glass does not vary with part size, small glass parts (glass fibers, for example) exhibit strengths very much higher than relatively larger parts. Large parts have more and larger flaws, increasing the probability that a severe flaw will coincide with a region of high tensile stress. This phenomenon leads to a lower breakage strength for larger glass parts.

2. Moisture. Glass parts which have been dried and tested in a vacuum exhibit higher strengths than those tested in the presence of moisture. This behavior has been predicted from the "stress corrosion theory." It is important to note that the small amount of moisture normally present in the atmosphere is sufficient to account for most of this effect. Therefore, it will not be necessary to differentiate between the strength of glass parts in wet versus dry atmospheric conditions during normal outdoor exposure.

3. Surface Damage. The strength of glass parts may be expected to deteriorate with time due to environmentally induced damage resulting from handling, shipping, installation, cleaning, hail and rock impact, sandstorms and other causes. Beason and Dalgliesch (References 2 and 3) have indicated that there is evidence of a reverse effect as well in which severe stress concentrations at the tips of sharp microcracks are supposedly alleviated by rounding off those cracks for which the stress corrosion is not made highly directional by a large applied stress.

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4. Duration of Load. Glass parts will sustain loads for short periods of time which will result in eventual failure. The existing flaws in the glass grow under the influence of a sustained load. When these cracks reach some critical size, failure occurs.

FACTORS INFLUENCING THE STRENGTH OF GLASS

A brief discussion of the factors influencing the failure of glass, adapted from Brown (Reference 4), is included here. In 1921 Griffith noted the weakening effect of preexisting flaws or scratches in the glass surface. The high stresses at the tips of these flaws account for the fact that the measured strength of glass in tension is usually several orders of magnitude lower than its theoretical strength. Deliberate surface conditioning of the glass surface by various investigators has borne out Griffith's observation. Surface roughening reduces the mean strength and variability. Polishing increases the mean strength and variability. The measured strength of glass samples tested in moist air decreases with increased duration of loading. It is now generally accepted that slow flaw growth takes place as a result of stress corrosion. The mathematical model describing the dependence of glass failure on load duration and loading proposed by Brown (Reference 4) has been adopted by Beason (Reference 2) and Dalgliesh (Reference 3) in the following form.

$$\int_0^{\tau_B} \left[\sigma(\tau)\right]^{\alpha} d\tau = \text{constant} \qquad (1)$$

where

τ = time

τ_B = time to break

$\sigma(\tau)$ = applied, time-variant stress

α = an empirically determined constant which depends on the surface condition of the glass, relative humidity and temperature.

With these factors considered, a quantitative assessment of the effect of glass temper, time duration of loading, glass surface area, and probability of failure is presented in the following paragraphs.

A. EFFECT OF TEMPER AND LOAD DURATION

As discussed above, the breakage strength of glass decreases as the duration of loading increases. For a constant applied stress Equation 1 may be written in the form

$$\sigma_B \propto \left(\frac{1}{\tau_B}\right)^{\frac{1}{\alpha}} \qquad (2)$$

where

σ_B = breakage strength

τ_B = time to break

α = an empirically determined constant, applicable only over a narrow range of load durations where it fits the data.

Dalgliesh (Reference 5) reports values of α for annealed glass from 12 to 20. Dalgliesh does not recommend a value of α for tempered glass. Shand (Reference 6) states that not only is tempered glass stronger initially, but the decrease in the breaking strength of tempered glass with load time is significantly less than that for annealed glass. This implies that the value of α would be significantly higher than 20.

For the simple power law (Equation 2) just discussed, the fracture stress approaches zero for loads of very long duration. This is at odds with the widely accepted idea that there is a level of applied stress, called the "endurance limit," below which crack growth will not occur. At levels of applied stress less than the endurance limit glass parts should be able to sustain loads for an indefinite period of time. Figure 1, reproduced from Shand (Reference 6), shows the breaking stress versus the duration of that stress. These curves are consistent with the concept of an endurance limit in that they tend toward some asymptotic lower bound of the breaking stress for long-term loading. Unfortunately, these curves extend only to a load duration of 10^7 seconds (approximately 4 months), whereas to properly consider deadweight load, we need load durations up to the design life of the glass plates (that is, greater than 20 years). Also, it should be noted that Shand (Reference 6) does not specify the size of the glass specimens on which Figure 1 is based.

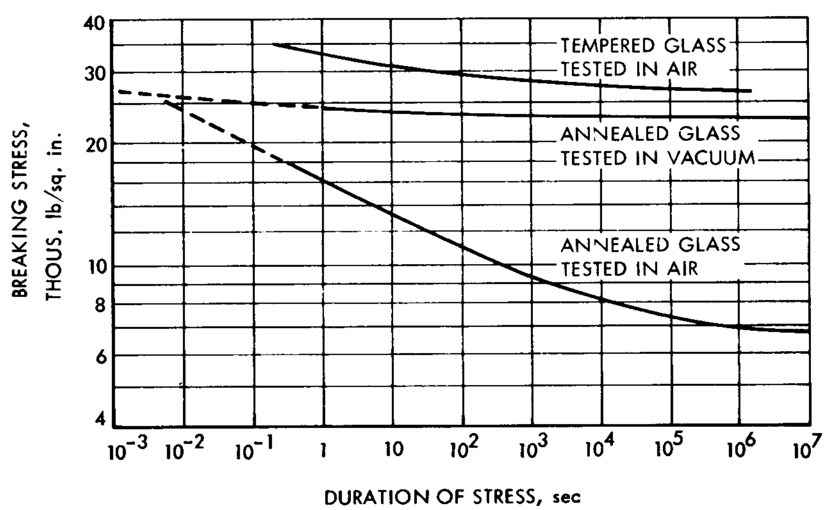

Figure 1. Stress-Time Characteristics of Glass Broken in Flexure Tests at Room Temperature (Composite Curves)

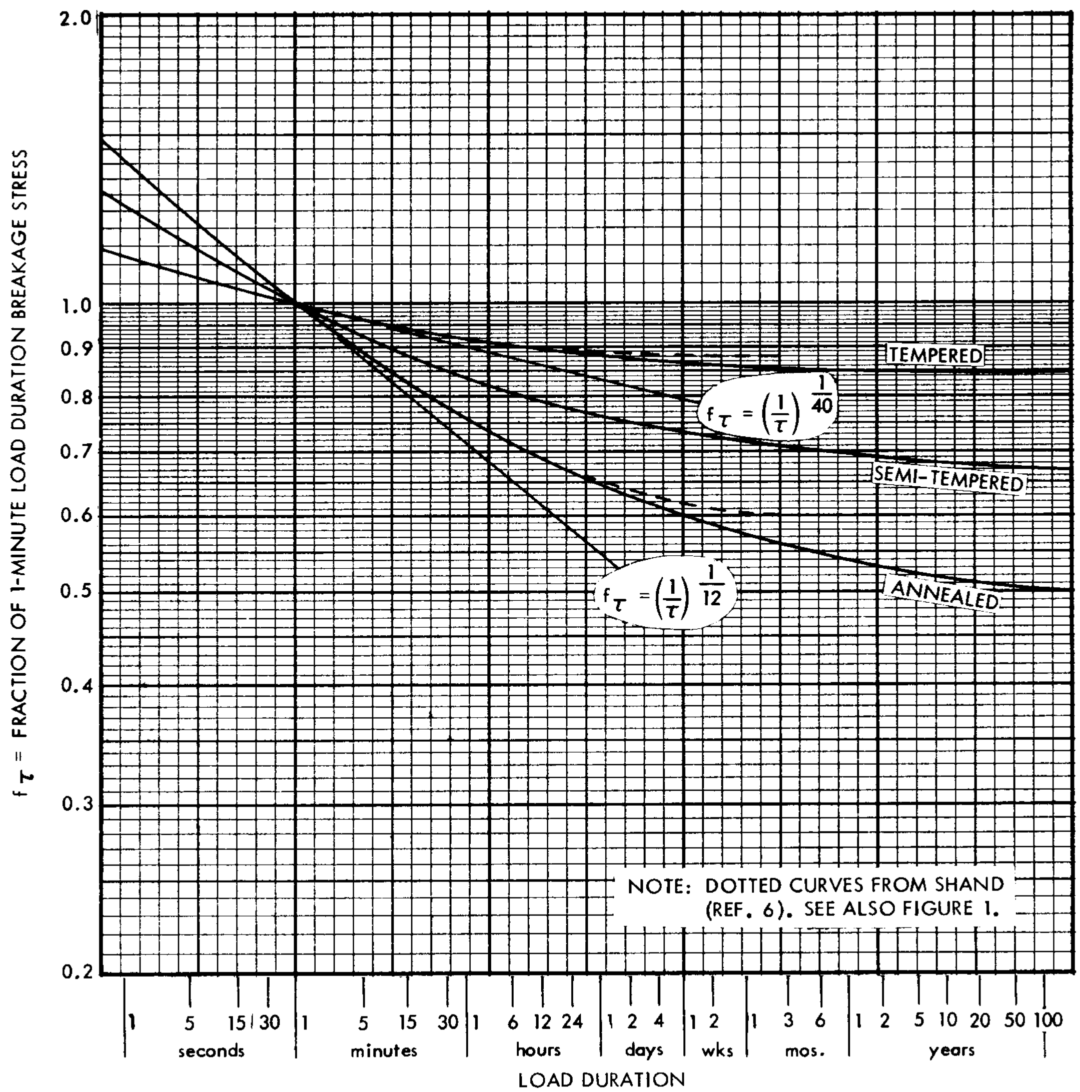

Figure 2. Fraction of 1-Minute Load Duration Glass Breakage Stress versus Load Duration

Therefore, it is the relative strength of annealed glass versus tempered glass and the decrease in strength with time that are of interest here.

The curves shown in Figure 2 have been extrapolated to a load duration of approximately 100 years and normalized to a value of unity for the 1-minute breaking stress of the glass. Shand (Reference 6) has stated that the endurance limit for (annealed*) glass is of the order of 40 to 45 percent of the 5-second breaking strength. The curve for annealed glass (Figure 2) has been faired to a value of about 40 percent of the 5-second breaking strength at 100 years load duration. This is somewhat less than if Shand's original curve (see dotted line - Figure 2) had been simply extrapolated to longer load durations. Likewise the curve for tempered glass shown in Figure 2 is somewhat lower at long load durations than Shand's original curve (shown dotted). To obtain strength-versus-time values for semi-tempered glass, the values for annealed and tempered glass have, arbitrarily, been averaged. The resulting values for semi-tempered glass are shown as a dot-dash curve in Figure 2. The equation $f_\tau = ({}^1/\tau)^{1/12}$ is also plotted in Figure 2. This equation is equivalent to Equation 2 and shows that for load durations between 5 seconds and 1 minute the value of α equal to 12 provides an excellent fit to the annealed glass curve. Likewise, a value for α of 40 provides an excellent fit to the tempered glass curve for load durations between 5 seconds and 5 minutes.

B. EFFECT OF PLATE AREA

As mentioned earlier, large glass parts fail at lower applied stress levels than do small glass parts. This is true because the likelihood that a flaw in the glass will coincide with a region of high applied stress is greater for larger parts. These flaws exist in newly manufactured glass and their size and/or number increase with time due to handling, missile impact and other loads. In the vast majority of cases, failure originates from surface flaws so that the area of a glass plate represents the pertinent measure of part size. Dalgliesh (Reference 5) reported that laboratory tests on glass plates have shown that the breaking strength varies inversely as the fifth to seventh root of glass surface area.

$$\sigma_B \propto \left(\frac{1}{A} \right)^{\frac{1}{6}} \qquad (3)$$

For the purpose of the design method presented herein, it is expedient to define the fraction, f_A, which is the fraction of the breaking stress of a 1-square-meter plate which will be attained by a plate of area A if both plates break 1 minute after the sudden application of the full load. From Equation 3 the fraction f_A may be expressed mathematically as

$$f_A = \left(\frac{1}{A} \right)^{\frac{1}{6}} \qquad (4)$$

where

f_A = fraction of the breaking stress of a 1 square meter plate which will be attained by a plate of area A

A = area of plate for which breaking stress is unknown (expressed in square meters)

Equation 4 is plotted on Figure 3.

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*It is assumed that Shand means annealed glass since he further states that the decrease in the breaking strength of tempered glass with increasing load duration time is significantly less than that for annealed glass.

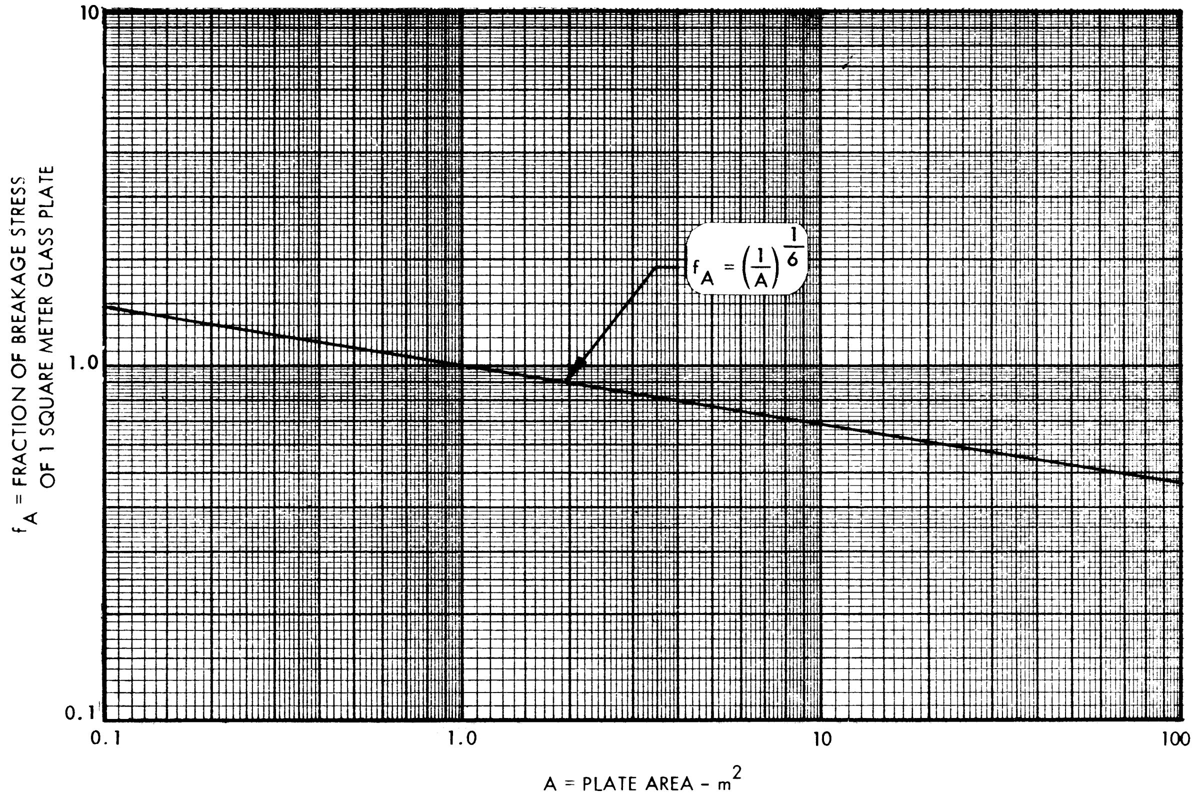


Figure 3. Fraction of Breakage Strength of 1-Square-Meter Glass Plates versus Plate Area

C. BREAKAGE STRENGTH VERSUS PROBABILITY OF FAILURE

In the following paragraphs the glass plate breakage data of other investigators is reanalyzed to obtain the glass breakage strength as a function of the probability of failure.

1. Selection of Glass Plate Breakage Data 10

To obtain a practical value for the breaking strength of glass to be used in determining the required thickness of photovoltaic solar panels the raw data of Bowles and Sugarman (Reference 8), Beason (Reference 9), and Wilson (Reference 10) have been analyzed employing Weibull statistical analysis techniques. The data of these investigators are preferred for the following reasons:

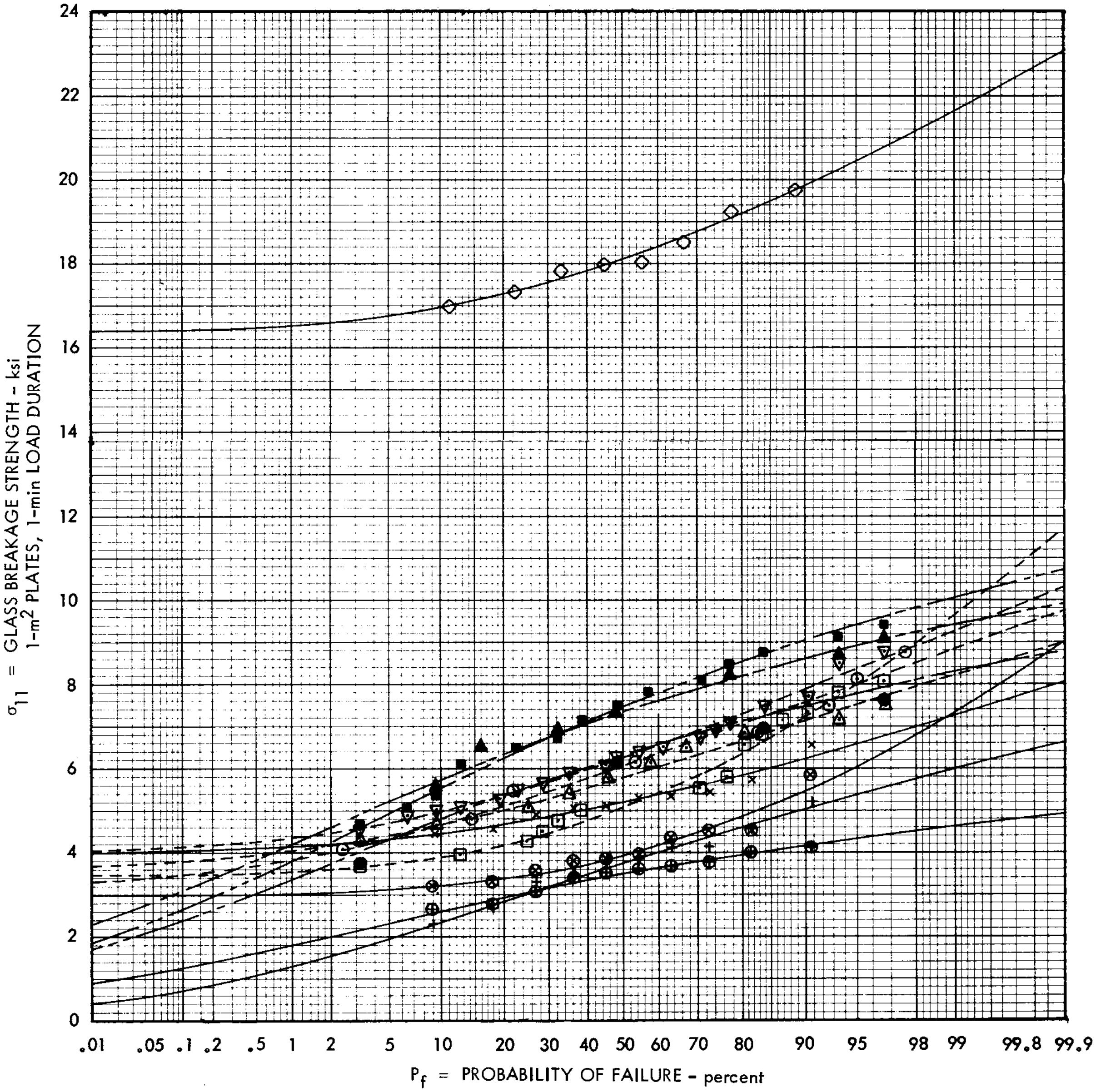
9 (a) The size of the samples tested is intermediate between the smallest and largest glass photovoltaic modules being considered. Bowles and Sugarman tested 41-inch square glass plates. Beason tested 28.5 x 60.5-inch plates and 28.5-inch square plates. Wilson tested 48-inch square plates.

(b) These investigators employed edge constraints which approximate a simply-supported condition.

(c) The load-time history prior to panel failure is necessary to make a meaningful assessment of the breaking stress for other load-time histories. The load-time histories from these data sources are known reasonably well. Bowles and Sugarman loaded the panels with a pressure load which increased approximately as the second power of time. They adjusted the loading mechanism so that the average pressure resulting in failure was reached 30 seconds after the start of the test. Beason's raw data are more definitive in this respect. His data include a complete pressure-time history for each sample of glass tested, as does Wilson's.

(d) These investigators tested a sufficient number of samples for the results to be statistically significant. Bowles and Sugarman tested 40 samples of .122-inch-thick annealed plate glass, 30 samples each of .197, .250, .373-inch-thick annealed plate glass and .110, .158, .195-inch-thick annealed sheet glass - all 41 inches square. Beason tested 20 samples each of .219 x 28.5 x 60.5-inch and .219 x 28.5 x 28.5-inch annealed sheet glass. In Beason's tests the 20 samples of each size were divided into 10 samples with the weathered side in tension and 10 samples with the indoor side in tension. Wilson tested 8 samples of .125 x 48 x 48-inch tempered float glass.

(e) The Bowles and Sugarman tests were performed on new annealed sheet and plate glass as noted above. Beason's tests were performed on "weathered" glass, removed from the Great Plains Life Building, Lubbock, Texas. This glass had been in service for about 20 years at the time of its removal for testing; it is believed to be annealed sheet glass. Wilson tested new tempered float glass.



Glass Type	Investigator	Glass Plate Size (inches)	Normalized Data (Tables 8-14) $P_f = \frac{n}{N+1}$	Best Fit Weibull Curves $P_f = 1 - e^{-\left(\frac{\sigma_{11} - \sigma_u}{\sigma_o}\right)^m}$ Line	σ_u psi	σ_o psi	m	C.C.*
New Annealed Plate Glass	Bowles and Sugarman (Ref. 7)	0.122 x 41 x 41	○	------	3205	3258	2.8187	.992
		0.197 x 41 x 41	△	------	3656	2471	2.5214	.995
		0.250 x 41 x 41	▽	------	3499	2057	1.3985	.991
		0.373 x 41 x 41	□	------	4044	2600	2.1961	.997
New Annealed Sheet Glass	Bowles and Sugarman (Ref. 7)	0.110 x 41 x 41	●	—-—	0	6617	6.9049	.936
		0.158 x 41 x 41	▲	—-—	0	7673	7.7111	.986
		0.195 x 41 x 41	■	—-—	0	7892	6.3892	.996
Weathered Annealed Glass	Beason (Ref. 8)	0.219 x 28.5 x 60.5	x } Weathered Side	——	4039	1393	1.8402	.980
		0.219 x 28.5 x 28.5	+ } Convex	——	0	4121	4.1036	.989
		0.219 x 28.5 x 60.5	⊗ } Weathered Side	——	3008	1250	1.2370	.987
		0.219 x 28.5 x 28.5	⊗ } Concave	——	0	3679	6.7021	.979
Tempered Float Glass	Wilson (Ref. 9)	0.125 x 48 x 48	◇	——	16395	2129	1.6887	.991

*Correlation Coefficient (C.C. = 1 Means Perfect Fit)

Figure 4. Breakage Strength versus Probability of Failure for Simply Supported, Glass Plates subjected to a Uniform Normal Pressure (Normalized to 1 m² Surface Area and 1-Minute Load Duration)

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